

Electromagnetic Mechanism for the Origin of Knots in Parsec Scale Jets

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Abstract. We consider the propagation and stability of the helical electromagnetic perturbations in a relativistic force-free Pointing flux dominated jet (magnetic helix). Perturbations are found to dissipate energy in the vicinity of the resonant surfaces inside the jet, where the resonance of the perturbation with the Alfvén waves occurs. The energy of the perturbations is converted into the energy of accelerated particles, which emit synchrotron radiation. The intensity and polarization of this radiation is modulated with the perturbation. Perturbations with vanishing group velocity are the most important and could be associated with the bright knots in parsec scale jets.

The jets from Active Galactic Nuclei are not uniform. They consist of a number of bright knots with fainter emission in between. There is mounting observational evidence that jets in many AGNs are dominated by electron-positron pairs. Many jets from AGN are highly collimated, stable over distance much exceeding their radii, and have superluminally moving knots. The hydrodynamic and MHD stability of jets was investigated in many studies, which generally find jets to be unstable. The jets are surrounded by gas. In case of light strongly magnetized force-free jets, the presence of surrounding gas changes the stability properties of the jet dramatically. The stability of the electron-positron jets, rotating and moving with relativistic speed and surrounded by a dense medium was studied by Istomin & Pariev (1994) and Istomin & Pariev (1996). Such jets were shown to be stable with respect to axisymmetric as well as spiral perturbations. The density of the media surrounding the jet, ρ , should satisfy the condition $\rho \gg B^2/(4\pi c^2)$ for the inertia of surrounding gas to stabilize the relativistic jet. On parsec scales, a typical value of $B \sim 10^{-2}$ G gives a proton density $n \gg 0.05 \text{ cm}^{-3}$. The characteristic density of gas in galactic nuclei is $n \sim 10 \text{ cm}^{-3}$. Therefore, the approximation of stationary jet walls used by Istomin & Pariev (1994, 1996) is well justified.

Surrounding gas stabilizes light force-free jets. Magnetic helices can have dominant toroidal magnetic fields and still be stable over long distances. Recent observations of the gradients and sign of the rotation measure across the jets in several BL Lac objects suggest the presence of the intrinsic toroidal magnetic field in the jets (Gabuzda & Murray 2003). The change of the direction of the magnetic field from toroidal close to the jet axis to axial on the periphery was inferred from the VLBI polarization measurements in blazar 1055+018 (Attridge et al. 1999). This change is also a characteristic of a spiral magnetic field.

How bright knots can be produced in a force-free magnetic helix? Alfvén and fast magnetosonic speeds are equal to speed of light in force-free electrodynamics. Therefore, even very relativistic flows inside jets are always subsonic. Shocks do not develop in the expanding subsonic flow. Thus, knots are not associated with shocks. Two possibilities remain then: 1) knots are perturbations of magnetic field propagating along the jet; 2) knots are the sites of particle acceleration, i.e. “illuminated” portions of magnetic helix. It turns out that these two possibilities are not independent: particle acceleration naturally occurs whenever a generic disturbance of electromagnetic fields propagates along the jet. Below we briefly summarize the results of our works Beresnyak, Istomin & Pariev (2003) and Pariev, Istomin & Beresnyak (2003), where all relevant details and more extended discussion can be found.

The energetic particles accelerated in the central region cannot survive far along the jet because of the synchrotron losses. Recent discoveries of X-ray and optical emission from a number of jets (e.g., Marshall et al. 2001; Harris et al. 2003) make the need for *in situ* particle energization even more essential. It is very tempting to utilize large scale electric fields present in a force-free relativistic jet to accelerate particles to high energies. However, because of high conductivity of plasma the electric field is directed perpendicular to the magnetic field and does not readily produce acceleration.

In a stable jet, perturbations do not increase with time ($\text{Im } \omega = 0$) or have a small decay rate ($\text{Im } \omega \approx 10^{-2} \text{Re } \omega$) because of the resonance with Alfvén waves $\omega' = k'_{\parallel} c$. When the specific energy density and pressure of the plasma are much less than the energy density of the magnetic field, the Alfvén velocity is equal to the speed of light in vacuum c (ω' and k' are the frequency and the wave vector in the plasma rest frame). The resonance condition is fulfilled on the specific cylindrical magnetic surface in the case of a cylindrical jet. For each ω' the position of the resonance surface is different (it also depends on the discrete azimuthal and radial numbers of the eigenmode).

The source of the disturbances is most likely non-stationary processes in the magnetospheres of the black hole and the accretion disc in the “central engine”. Short time variability on scales from days to months is actually observed in AGN. The spectrum of this variability is a broadband as there is no clearly identified periodicity. As was shown in Istomin & Pariev (1994, 1996) a standing eigenmodes ($v_{\text{group}}(\omega_s) = 0$) generally exist in relativistic jets with toroidal magnetic fields, which do not propagate along the jet but are only subject to diffuse spreading. While all other disturbances, with $\omega \neq \omega_s$, propagate away, the disturbances with the frequency close to ω_s do not. Their amplitude grows and much exceeds the amplitude of all other disturbances. Therefore, the perturbations become close to monochromatic (for a given discrete azimuthal and radial

numbers) and the Alfvén resonance surface corresponding to the frequency of the standing wave ω_s is formed.

In the vicinity of that surface the magnetic and electric fields of the wave are large. Particles in the jet are accelerated by the electric field there, drifting away from the region of the strong fields and absorbing the energy of the perturbation. Thus, the stability of the jet is directly related to the production of energetic particles in the jet: the perturbation is damped with a small damping rate. Wave crests of the standing modes move along the jet and can be identified with the bright knots with typical sizes of the order of the wavelength of the standing wave, which is about the radius of the jet.

The polarization of synchrotron emission in knots is very sensitive to the geometry of the helical large scale magnetic field. VLBI observations provide evidence for the polarized emission in knots and in the space between knots. This is indicative of the existence of a large scale magnetic field all over the jet rather than concentrated in separate knots. The polarization of synchrotron emission of parsec scale jets is being studied by few groups (Gabuzda 2000; Leppänen et al. 1995; Lister 2001). We used observational data on quasars and BL Lac objects to compare with our calculations of polarizations and proper motion of knots in our electromagnetic model described above. All relativistic effects were taken into account. We found that if the emitting particles are distributed uniformly across the jet, observational data cannot be matched. If the particles are concentrated in the vicinity of the Alfvén resonance surface, the polarization properties are changed dramatically, and predictions of our model does not contradict to the observational data.

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